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A Gauge to Measure Mass Flow Rate of Sap in Stems and Trunks of Woody Plants

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Abstract. **A stem flow gauge designed for herbaceous plants was adapted for measuring the absolute mass flow rate of sap in large stems and trunks of woody plants. The method uses a steady-state heat balance method in which a constant, known amount of heat is supplied to a stem segment. The axial and radial conductive heat fluxes away from the heated segment are measured, as well as the rise in sap temperature. The device can be operated by commonly available dataloggers and does not require calibration. In a greenhouse experiment with a small tree, the sap mass flow rate, as measured by the the gauge, agreed with the measured transpiration rate within 4% when both were integrated over 24-hr periods or longer. Short term comparisons (≤4hr) were less accurate, due to the changes in water content of the tree above the gauge, which cause a lag between transpiration rate and sap flow rate. The dynamic response of the tree and gauge system to sudden changes in sap flow was ≈20 min under midday conditions. Other than the insertion of temperature-sensing thermocouples 2 mm into the trunk, the gauge components are non-invasive and do not disturb the tree physically or physiologically to a significant extent.**

Adding heat to the moving sap of plants as a means of measuring the sap flux is not new. Huber's (8) work in in 1932 laid the foundation for what is currently referred to as the heat pulse velocity (HPV) technique. In this approach, the sap velocity is estimated from the time required for a heat pulse, injected into the xylem, to travel a finite distance downstream. Bloodworth (2), Closs (5), Swanson (22), Lassoie (12), Miller (13), and Cohen (6) have contributed to HPV theory and technique. The limitation of this approach is that only the sap velocity is measured. Calculation of sap flux (mass × time) from the sap velocity requires a knowledge of the active conducting area of the xylem, a figure difficult, if not impossible, to obtain, and not constant over time. Hence, the HPV method requires an empirical and variable conversion factor, obtained by recording the rate of water loss by weighing.

Direct measurement of the mass flow of sap with a stem heat balance (SHB) method, using a continuous application of heat, was first proposed by Vieweg and Ziegler (23), and later by Daum (7). A mathematical analysis of two-dimensional heat conduction and convection in a stem shows how the mass flow rate of sap can be obtained by accounting for heat inputs and outputs (15). At present, two forms of the SHB approach to measure sap flux directly have been reported. In the method developed for trees by Čermák and co-workers (3, 10), a constant temperature difference is maintained between sensors at and above the heated segment by varying the power of the heater. The accuracy of this method was recently demonstrated in the field by Schultze et al. (20). Such a gauge requires no calibration and has an almost instantaneous response to changes in sap flow. However, electrodes and temperature sensors must be inserted in the trunk, which limits its application to trunks of appreciable diameter. The maintenance of steady temperature gradients by varying the heat input requires sophisticated electronic proportional control of each individual gauge (10).

An alternative SHB method, first described by Sakuratani (18, 19) and further developed by Baker and Van Bavel (1), maintains a constant heating power, allowing the temperature difference between sensors above and below the heater to vary. Because of its development for use with herbaceous plants of smaller diameter (8 to 20 mm), the sensors were all located on the outer surface of the stem. The method requires a zero-set procedure, but otherwise is an absolute measuring technique and does not need calibration. However, due to the time needed to establish steady-state conditions, a lag can occur between stem flow change and gauge response (1). Commonly available dataloggers can record and process the signals from several such gauges at one time.

The second approach to the SHB method is simpler and cheaper than the first. In principle, it could be applied to larger diameters typical for stems or trunks of woody plants. However, some assumptions underlying the method may not apply to the larger diameter of trunks and the lag in response can be expected to be larger. The purpose of our work was to evaluate a SHB gauge design adapted for application to trunk diameters up to 50 mm. If sufficiently accurate, such a gauge would be useful for measuring water use in the field by small trees, for example. No satisfactory method exists at this time for this purpose.

Materials and Methods

*Theory.*The theory of the heat balance approach to sap flow measurement in herbaceous plants has been described in detail by Sakuratani (18, 19) and by Baker and Van Bavel (1). In brief, an insulated section of stem about as long as its diameter is heated externally at a constant rate, and the heat fluxes in the radial and vertical direction are measured (Fig. 1). Heat carried in the moving sap is calculated by subtracting measured conductive heat fluxes from the heat input as in Eq. [1].

$$q_f = q_i - q_u - q_r - q_d \qquad [1]$$

where: q_f = heat carried in the moving sap (W); q_i = heater input (W); q_u = heat flux by conduction above the heater (W); q_r = radial heat flux by conduction (W); and q_d = heat flux by conduction below the heater (W).

Equation [2] is the pertinent equation for calculating the mass

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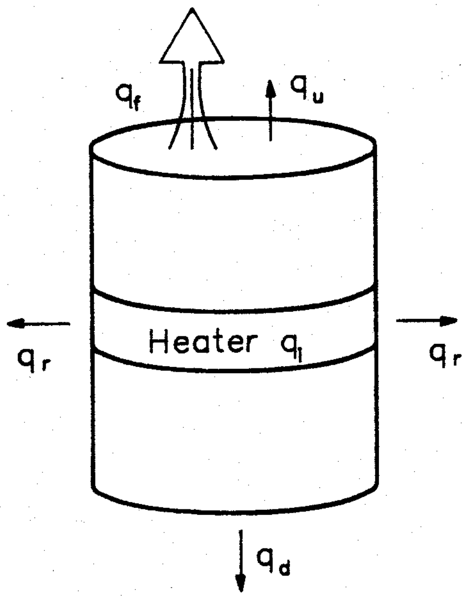

Fig. 1. Diagram for the heat balance method for measuring sap flow in a tree trunk. The 20-mm-wide heater completely encircled the trunk. Outer insulation is not shown. Symbols refer to Eq. [1].

flow of water or sap from the actual power input and from measured values of temperature gradients.

$$F = \frac{\{P - K_{st} \times A[(dt_d + dt_u)/dx] - K_{sh} \times E\}}{C_p \times dt_{ud}} \qquad [2]$$

where (referring to Fig. 2): F = sap flow rate ($g \cdot s^{-1}$); P = power to heater (W); K_{st} = thermal conductivity of the stem ($W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$); A = cross section of stem (m^2); dt_d = temperature difference between thermojunction pairs below the heater (°C); dt_u = temperature difference between thermojunction pairs above the heater (°C); dx = distance between upper and lower thermojunction in each pair (m); K_{sh} = sheath conductance ($W \cdot mV^{-1}$)(defined in text); E = voltage output of radial thermopile (mV); dt_{ud} = temperature difference between upper and lower junctions nearest the heater (°C); and C_p = heat capacity of water ($J \cdot g^{-1} \cdot {}^{\circ}C^{-1}$).

The thermal conductivity of the stem (K_{st}) was obtained using a method described by Sakuratani (17), adapted to the case of a woody trunk, where:

$$K_{st} = K_{wood}V_{wood} + K_{water}V_{water} + K_{air}V_{air} \qquad [3]$$

where: K = thermal conductivity ($W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$) and V = volume fraction (%).

The relative volume occupied by wood (V_{wood}) was obtained from Kramer and Kozlowski (9), that occupied by water (V_{water}) from actual test samples, and that of air (V_{air}) as the remainder. The thermal conductivity of the dry wood was the average of values given for wood with a density similar to that of the test samples (16). The conductivity of air and water were obtained from standard physics tables. Using this method, a K_{st} value of 0.42 $W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$ was calculated.

The sheath conductance (K_{sh}) can be calculated from Eq. [2] when the sap flow (F) is at or near zero and solving for K_{sh}. Values of K_{sh} were measured in three ways: 1) using the lowest pre-dawn values for K_{sh} and assuming zero sap flow; 2) using the lowest values obtained when the entire tree canopy was enclosed in plastic and placed in the dark for several days, again assuming zero sap flow; and 3) values measured on the test tree trunk after it had been severed above and below the gauge to establish zero flow.

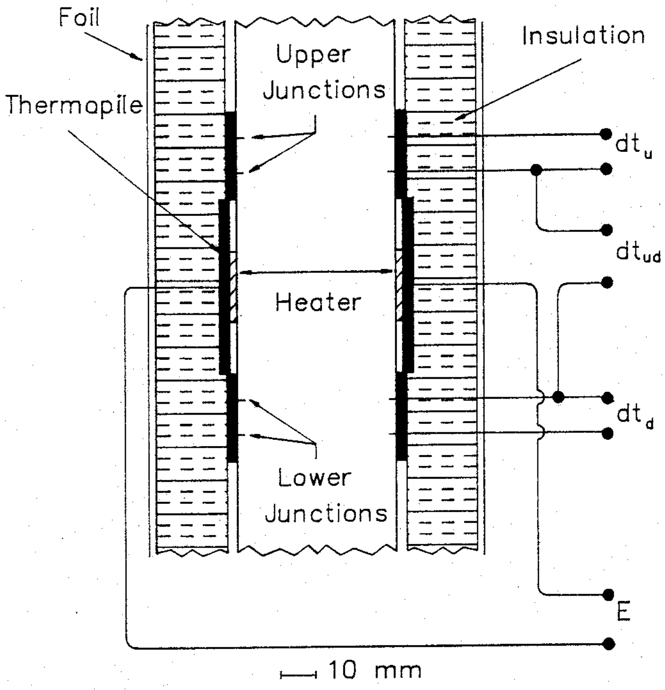

Fig. 2. Diagrammatic vertical stem cross-section of a tree trunk with gauge in place. The heater (hatched) and cork strips (solid black) extend around the entire trunk. There are four thermojunction pairs on both the upper and lower strips. The distance between junctions in each pair was 10 mm. The thermopile contained 18 thermojunctions, nine on each side. The insulation around the entire assembly was 20 mm thick.

Gauge design. Design and wiring of the gauge was based on that of Baker and Van Bavel (1), but adapted to fit the dimensions of the tree (Fig. 2). The heater was constructed of a length of pipe heating tape equal to the circumference of the tree. Although it is recommended that the length of the heated segment of trunk be equal to the trunk diameter (1, 18), in this test it was only 20 mm—the width of the pipe heating tape. A layer of heavy-duty aluminum foil, cut to the same dimensions as the heating tape, was applied to both sides of the tape to ensure more uniform heating. A regulated DC power supply was used to supply current to the heater. An estimate of the power requirements of the heater of 0.9 W was made, based on the power density [power (unit surface area)$^{-1}$] used previously (18, 19). The power actually used was 0.880 ± 0.002 W.

Cork and neoprene gasket material (3 mm thick) was the flexible support for all thermocouple junctions. The thermocouples were constructed of 0.25- or 0.38-mm-diameter (30 and 26 AWG) copper and constantan wire. A strip of cork 50 × 145 mm served as the thermopile backing. There was a total of 18 equally spaced junctions, nine on each side. Transparent tape was placed over the junctions on the inner side of the thermopile so that no contact would be made between the thermocouple junctions and aluminum foil covering the heating tape.

Two 25 × 145-mm cork strips served as the supports for the up- and downstream thermojunctions. In each case, four pairs of junctions were evenly spaced on the strip, 10 mm apart vertically. Each pair of junctions was wired in parallel with the other three so that the voltage output represented the arithmetic average of all four pairs (14). Due to the presence of rough, thick bark on some trees, the thermocouple junctions were constructed so that they could be inserted 2 mm into the bark, ensuring good contact between the sensors and wood. Holes for the thermocouples were made with a small piece of wood containing two nails protruding 2 mm and placed exactly 10 mm apart. The nails were of similar diameter as the thermocouple junctions. The distance between the center of the thermopile and of the up- or downstream strip was ≈35 mm. The strips were placed on the tree and the distance was adjusted to avoid knots or other rough areas of the trunk. A separate thermocouple was inserted between the heater and trunk to record the trunk temperature.

After the sensors were put in place, they were covered with a 20-mm-thick tape of Armaflex insulation, extending ≈250 mm above and below the sensors. The entire assembly was covered with aluminum foil to reflect solar radiation and to keep the trunk at a more uniform temperature.

A CR21X (Campbell Scientific Corp., Logan, Utah) datalogger was used to record all measurements. The first four analog channels were used for the differential voltage measurements of the gauge outputs. Analog channels 5 and 6 measured the voltage to the heater and temperature at the heater, respectively. The datalogger was programmed to record and interpret the output from all sensors every 30 sec and to compute and store 5-min averages on cassette tape. A wiring diagram is shown in Fig. 3.

Experimental procedure. The accuracy of the gauge was tested in a greenhouse on the campus of Texas A&M Univ., College Station during Dec. 1987 and Jan. 1988. A potted *Ficus benjamina* tree with a trunk diameter of 45.2 mm and leaf area of 6.1 m^2 was used as the test tree. During the tests, the tree was kept well-watered at all times by placing the pot inside a plastic container in which ≈15 mm of standing water was maintained. Pot and plastic container were covered with plastic so that the water loss from the system was due to transpiration only. Three to four times daily, at 0800, 1230, 1700, and 2100 HR, the tree was weighed with a KTron balance, accurate to 1 g on a 30-kg range. In addition, the tree was weighed before and after adding water to the system.

The gauge was tested for several 3- to 5-day periods under normal sap flow conditions. A few leaf resistance measurements were made with a LI-COR LI1600 steady-state porometer. During one test, the entire tree was enclosed in plastic and kept in the dark to reduce sap flow to near zero. In the final test, the roots and leaves were removed, leaving only a 600-mm segment of trunk containing the gauge. The cut ends of the trunk were covered with petrolatum to retard water loss and the gauge was tested at zero sap flow. The leaf area and volumetric water content of the wood were determined at the same time.

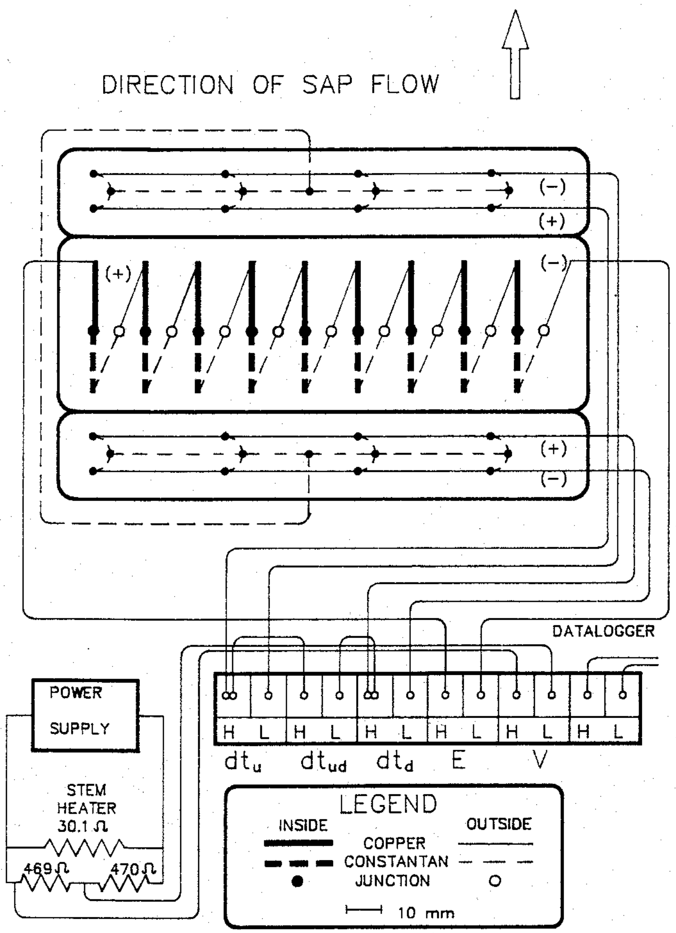

Fig. 3. Wiring diagram of the sap flow gauge. About 5.2 V is provided to the heater to produce a power input of 0.88 W. The signal to the data logger is divided by two because the range of the latter is limited to 5 V. The thermopile thermojunctions were threaded into the center cork strip.

Table 1. A comparison of sheath conductance values (K_{sh}) of a 45-mm-diameter trunk sap flow gauge, obtained by three different methods.

Calendar day and year	Method	K_{sh} ($W \cdot mV^{-1}$)
335–338 (1987)	Lowest pre-dawn value	0.762
345–348 (1987)	Tree covered with plastic, in darkness	0.798
19–25 (1988)	Lowest pre-dawn value	0.754
28 (1988)	Excised trunk	0.774

Results and Discussion

Sheath conductance (K_{sh}) values obtained by the three methods discussed earlier are listed in Table 1. Although care was taken to apply the gauge components in the same manner for each test, conditions could not be duplicated exactly. In addition, more than a month elapsed between the first and last tests, during which time subtle physical qualities of the tree, such as wood water content, may have changed and caused some variation in K_{sh}. The value calculated from true zero sap flow after each use of the gauge, and, without removing or changing gauge components, should be the most accurate. However, destruction of the test tree may not be practical or desirable, especially in the case of large trees. Enclosing the tree leaf area in plastic reduced sap flow to 3 to 4 $g \cdot hr^{-1}$, very near to zero. Due to the large surface area of plastic, it was impossible to stop all water loss from the system. In trees with canopies larger than the one used here, enclosing the leaf area in an air-tight cover would be impractical. Hence, the use of minimum pre-dawn values for K_{sh} has much to recommend itself.

In any case, the lowest pre-dawn values of K_{sh} under normal conditions were not greatly different from the other two estimates for zero flow (Table 1). The average measured water loss at night ranged from 5 to 8 $g \cdot hr^{-1}$. Although sap flow continued in the early evening to recharge water lost from the canopy during the day, by early morning it had fallen to near or below the measured night-time average. Because these values are so low in comparison to midday values of near 100 g·hr^{-1}, little error is introduced by assuming these levels as zero for the purpose of calculating K_{sh}. Furthermore, a sensitivity analysis of K_{sh} showed that, even if K_{sh} were in error by 10% or 20%, only a 4% or 9% error in the sap mass flow rate would result. As pre-dawn values of K_{sh} can be obtained *in situ* while a test is proceeding, they were used in all further analysis of gauge performance.

The accuracy of the gauge was found by comparing the sap mass flow measurements of the gauge with water loss by transpiration measured by the balance. The cumulative water loss from the tree found by the two methods is compared for the two test periods (Fig. 4). The values found with the gauge agreed within 4% with the recorded weight loss, a significant improvement over the 10% figure reported by Baker and Van Bavel (1) and by Sakuratani (19). A double-mass plot can obscure deviations that occur over short periods of time. In woody plants, sap flow and transpiration may differ appreciably. The trunk and branches of a tree constitute a considerable water capacitance that may cause a lag between changes in transpiration and sap flow. The single mass plots in Fig. 5 show that the change in sap flow always lagged the change in transpiration. This lag is even more apparent in Fig. 6, where short-term comparisons between sap mass flow and transpiration values are made for each of the two test periods. During the morning hours (0800–1230 HR) transpiration always exceeds sap mass flow, while, during the afternoon (1230-1730 HR) and night-time hours (1730–0800 HR), the reverse is true. Such a lag between sap mass flow and transpiration was not reported for either cotton or sunflower, both herbaceous plants (1). Therefore, to get the most accurate estimates of transpiration of woody species, gauge data should be integrated for at least one 24-hr period, preferably from pre-dawn to pre-dawn, so as to compare similar states of hydration. In cases where a tree is recovering from dehydration, even one 24-hr period may not be long enough. These precautions apply in a like manner to the SHB method of Čermák et al. (3).

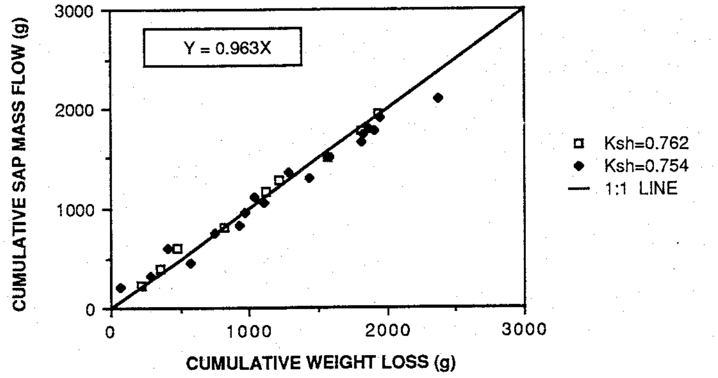

Fig. 4. Plot of cumulative sap flow measured by the gauge vs. cumulative transpiration water loss measured by the balance. The data represent measurements made during all test days. All tests were conducted in a greenhouse under ambient light and temperature conditions. The two K_{sh} values represent predawn values calculated for two separate tests. The regression through the origin was calculated by standard methods (21).

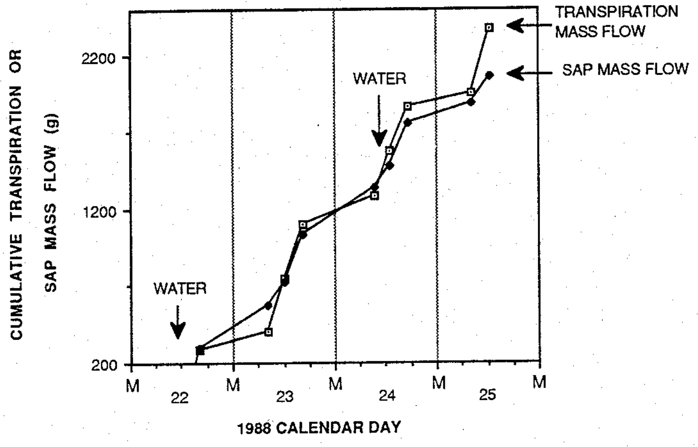

Fig. 5. Plot of cumulative sap flow, measured by the gauge and by the balance, from 22–25 Jan. 1988 (CDN 22–25). The value of K_{sh} was 0.754 W·mV^{-1}. M = midnight.

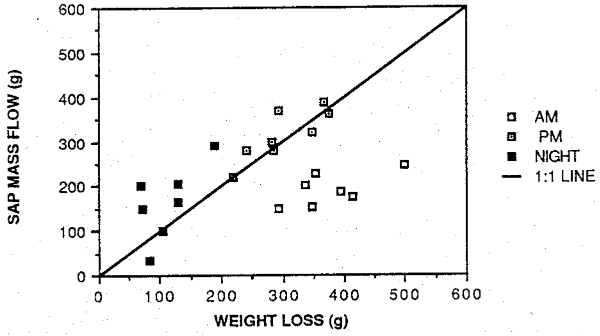

Fig. 6. Plot of short-term sap mass flow values measured by the gauge vs. corresponding transpiration values measured by a balance. AM readings were from 0800 to 1230 HR, PM readings from 1230 to 1730 HR, and NIGHT readings from 1730 or 2130 to 0800 HR.

Changes in water content of the wood will also influence the dynamic response of sap flow to a step change in conditions controlling transpiration, as already shown earlier (4, 11). In addition, there will be a lag between a change in sap flow and gauge response due to the relatively large heat capacitance of the trunk section. We evaluated the dynamic response of the tree and gauge system by calculating the time constant, the time required for the gauge to register 63.2% of the total response to a step change in transpiration. The time constant equals the slope of the linear regression of the natural log of the difference between actual and final sap flow values over time (1). On calendar day number (CDN) 25 (1988) the sap flow rate was steady at 80 g·hr^{-1} at 1245 HR. About one-half the leaf area of the tree was removed, and the sap flow allowed to reach a new steady value. The time constant was calculated to be 20 min. At higher flow rates, this value would be lower, and vice versa. A similar test was performed under zero flow conditions. Heating power was increased from zero to the test level of 0.88 W, and changes in radial thermopile output rather than sap flow were recorded. Under zero flow conditions the time constant was 76 min. For herbaceous species, the corresponding time constants are from 5 to 20 min (1).

The value of the midday time constant found here was slightly higher than that reported by Čermák (4), who found 10 to 12 min for a willow tree at sap flow rates higher than reported here, but lower than those reported by Landsberg (11) for an apple tree. We may conclude that the dynamic response of the system is not a critical factor, and should not be a problem in common application of the gauge. However, rapid changes in sap flow, such as might be caused by stomatal cycling or sudden changes in solar radiation, will not be detected, or will at least be dampened by the water capacitance of the tree above the gauge location and by the heat capacitance of the insulated part of the trunk. Hence, the method cannot be used to find accurate transpiration rates over short periods of time, however accurate the sap flow rate is established.

As an example of the diurnal course of sap flow, we show Fig. 7 for 2 Dec. 1987 (CDN 336). On those days, the sky was clear and the greenhouse air near 30C. The peak sap flow was 90 $g \cdot hr^{-1}$, a rather low rate for a tree with a leaf area of 6.1 m^2. However, a *Ficus benjamina* has stomata only on the abaxial side of the leaf. In addition, air movement in the greenhouse was low and measured stomatal resistance was relatively high, 1800 $s \cdot m^{-1}$. All of the foregoing facts explain the low rate of water loss.

In Fig. 8 we show the diurnal partitioning of the trunk heating power (0.88 W) on CDN 336. Vertical conduction of heat above and below the heater was slight, if not negligible, at all times during the day, a fact documented elsewhere for thermal flowmeters (24). Depending on the time of day, most of the heat loss was associated with the radial heat flux or heat transfer to the sap stream. To determine the importance of vertical heat conduction on gauge accuracy, sap mass flow rates were recalculated for the test days using only radial and sap heat fluxes. These values are compared with measured transpiration in Fig. 9. Sap mass flow differs by 17% from measured transpiration values because K_{sh} is overestimated by ignoring the vertical heat conduction. This can be seen by comparing the values for K_{sh} in Fig. 9 with those in Fig. 4.

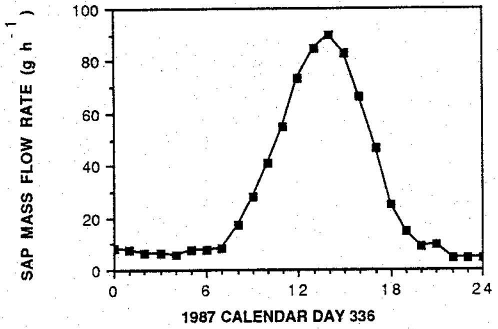

Fig. 7. Diurnal trunk sap flow pattern on CDN 336 (1987). Skies were clear and the midday ambient greenhouse temperature was 30C.

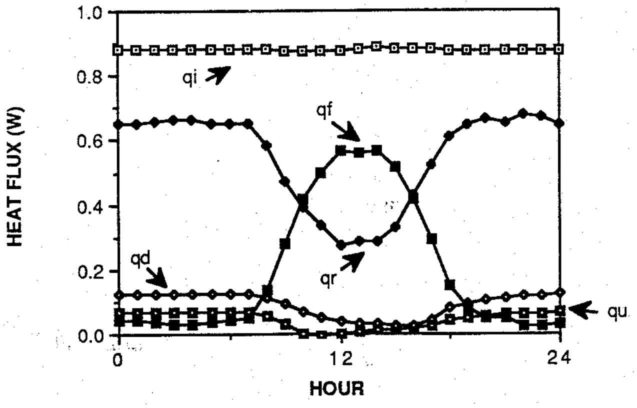

Fig. 8. Diurnal course of trunk heat fluxes on CDN 336 (1987), corresponding to Fig. 7. Heater input = q_i, heat flux by conduction above the heater = q_u, heat flux by conduction below the heater = q_d, radial heat flux by conduction = q_r, and heat carried in the moving sap = q_f.

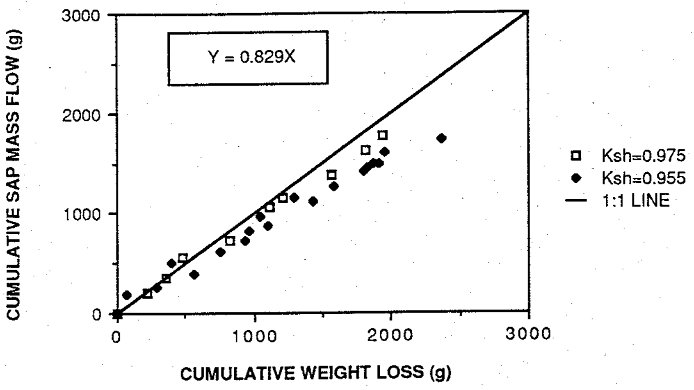

Fig. 9. Plot of cumulative sap mass flow measured by the gauge vs. cumulative transpiration water loss measured by a balance. Sap mass flow and K_{sh} were calculated neglecting vertical heat conduction. The regression through the origin was calculated by standard methods (21).

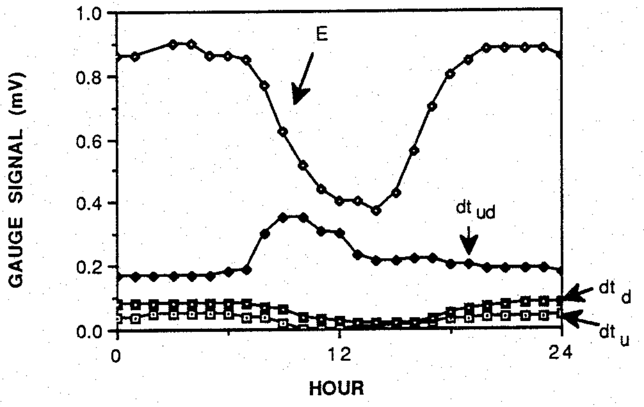

Fig. 10. Diurnal course of actual gauge signals measured on CDN 336 (1987), corresponding to Figs. 7 and 8. Heat conduction was the vertical heat conduction above (dt_u) and below (dt_d) the heater. Convective heat loss (dt_{ud}) was by the moving sap. Radial heat flux (E) was the heat lost radially through the gauge components and insulation.

Actual gauge signals and temperature gradients are listed in Table 2 for a period of maximum sap flow (CDN 336), and one of minimum sap flow when the tree was enclosed in a plastic bag (CDN 347). In both cases, all actual gauge signals are well above the minimum detection level of the CR21X, which is 0.0003 mV. Figure 10 shows the diurnal cycle of actual gauge signals for CDN 336. It is interesting to note that the maximal voltage (or temperature difference) vertically across the heater (dt_{ud}) occurs between 0900 and 1000 HR, while the minimal radial voltage (E) occurs at 1400 HR. Maximal sap flow also occurs near 1400 HR (Fig. 7). It is evident that both the radial heat loss and the heat transported by the sap are of comparable magnitude and that the accuracy of both numbers determines that of the gauge.

A separate measurement of trunk temperature at the heater

Table 2. Actual sap flow gauge signals and their corresponding temperature equivalents for a 2-hr period when sap flow was high (CDN 336) or low (CDN 347)[z].

	Gauge signal				Temperature equivalent[y] of gauge signal				
Time (HR)	dt_u (mV)	dt_{ud} (mV)	dt_d (mV)	E (mV)	dt_u (°C/mm)	dt_d (°C/mm)	dt_{ud} (°C)	Trunk at heater (°C above) (ambient)	Flow rate ($g \cdot hr^{-1}$)
					CDN 336				
1130	−0.002	0.285	0.028	0.41	0.000	0.07	7.1	5.1	64.0
1200	0.000	0.266	0.025	0.36	0.000	0.06	6.7	4.5	73.0
1230	0.000	0.240	0.021	0.38	0.000	0.05	6.0	3.9	79.0
1300	0.004	0.228	0.021	0.37	0.010	0.05	5.7	3.7	85.0
1330	0.006	0.221	0.020	0.37	0.015	0.05	5.5	3.6	87.3
					CDN 347[x]				
1130	0.040	0.191	0.072	0.88	0.100	0.18	4.8	14.8	3.0
1200	0.040	0.190	0.073	0.88	0.100	0.18	4.8	14.8	3.0
1230	0.040	0.189	0.073	0.88	0.100	0.18	4.7	14.8	2.6
1300	0.040	0.188	0.073	0.88	0.100	0.18	4.7	14.8	2.6
1330	0.040	0.186	0.073	0.88	0.100	0.18	4.7	14.8	2.5

[z] CDN = calendar day.

[y] Distance between thermocouple pairs (dt_d and dt_u) was 10 mm; distance between upper and lower junctions nearest the heater was 65 mm.

[x] The tree was kept in the dark and the canopy was enclosed in plastic.

showed a 4C rise over ambient temperature at flow rates of 80 $g \cdot hr^{-1}$ (Table 2). This rise is directly related to the flow rate and may be as much as 15C when the latter is small. The temperature rise did not appear to cause any physiological injury in the 3- to 5-day tests performed, but it is large and could be a problem during longer-term experiments or at higher ambient temperatures. We conclude that the initial estimate of the appropriate heating power proved to be too high. It could be reduced to one-fifth the level used without reducing gauge signals unduly, given the accuracy of the CR21X.

In any measurement technique, one wishes to avoid significant disturbance of the process being investigated while retaining adequate accuracy and sensitivity. The trunk flow gauge described here meets both criteria. Other than the insertion of thermocouples 2 mm into the trunk, all gauge components are noninvasive, remaining on the outer surface of the trunk. In stems or trunks with smooth bark or of a small diameter, insertion of the thermocouples may not be possible or necessary. They can be affixed to the cork backing as described by Baker and Van Bavel (1).

Temperature gradients produced by the continuously operating gauge can be adjusted, by varying the heater input, and be maintained within a physiologically safe range. Our tests were performed in a greenhouse under normal ambient light and temperature conditions. Though no corrections were made for natural diurnal temperature fluctuations of the air or trunk, the gauge gave accurate results. Sap flow rates were within 4% of transpiration loss, as found by weighing, provided the measurements were integrated over 2 to 3 days.

The gauge is simple and well-suited for use in the field, if protection against moisture or rain can be provided. It could become a useful tool in future studies of the water relations of woody plants. Our experience and the results of others with the SHB sap flow gauge are limited to diameters from 8 to 50 mm, and, for woody species, to a single tree type. Though additional tests are indicated, there is no evidence at present that would limit the range of application of the technique.

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